

UNITED STATES PATENT APPLICATION

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FOR

**A LOW POLARIZATION GAIN DEPENDENT SEMICONDUCTOR OPTICAL
AMPLIFIER WITH VARIABLE RESIDUAL CLADDING LAYER THICKNESS**

A LOW POLARIZATION GAIN DEPENDENT SEMICONDUCTOR OPTICAL AMPLIFIER WITH VARIABLE RESIDUAL CLADDING LAYER THICKNESS

RELATED APPLICATIONS

[0001] This application is also related to, and claims priority from, U.S. Provisional Patent Application Serial No. 60/443,534, filed on January 30, 2003, entitled "A LOW POLARIZATION GAIN DEPENDENT SEMICONDUCTOR OPTICAL AMPLIFIER WITH VARIABLE RESIDUAL CLADDING LAYER THICKNESS", the disclosure of which is incorporated here by reference.

BACKGROUND

[0002] The present invention relates generally to semiconductor optical amplifiers and, more particularly, to semiconductor optical amplifiers having low polarization gain dependency and methods of making such devices.

[0003] Technologies associated with the communication of information have evolved rapidly over the last several decades. Optical information communication technologies have evolved as the technology of choice for backbone information communication systems due to, among other things, their ability to provide large bandwidth, fast transmission speeds and high channel quality. Semiconductor lasers and optical amplifiers are used in many aspects of optical communication systems, for example to generate optical carriers in optical transceivers and to generate optically amplified signals in optical transmission systems.

Among other things, optical amplifiers are used to compensate for the attenuation of optical data signals transmitted over long distances.

[0004] There are several different types of optical amplifiers being used in today's optical communication systems. In erbium-doped fiber amplifiers (EDFAs) and Raman amplifiers, the optical fiber itself acts as a gain medium that transfers energy from pump lasers to the optical data signal traveling therethrough. In semiconductor optical amplifiers (SOAs), an electrical current is used to pump the active region of a semiconductor device. The optical signal is input to the SOA from the optical fiber where it experiences gain due to stimulated emission as it passes through the active region of the SOA.

[0005] Like other devices employed in optical networks, SOAs suffer from polarization sensitivity. That is, the gain experienced by a light beam that is input to a conventional SOA will vary depending upon the polarization state of the input optical energy. In this context, the polarization state of a light beam is typically described by the orthogonal polarization components referred to as transverse electric (TE) and transverse magnetic (TM). Unfortunately even if light having a known (e.g., linear) polarization state is injected into a typical optical fiber (i.e., a single mode fiber) after propagation through the optical fiber the light will become elliptically polarized. This means that the light input to SOAs placed along the optical fiber will have TE and TM polarization components of unknown magnitude and phase, resulting in the gain applied by SOAs also varying indeterminately as a function of the polarization state of the input light.

[0006] There are various techniques that have been employed to compensate for the polarization dependent gain that is introduced by SOAs. One such technique, shown in

Figure 1, is to arrange two SOAs in series. In amplifier 10, the gain for TE mode light is greater than the gain for TM mode light. Amplifier 12 has the same structure as amplifier 10 but is rotated by 90 degrees so that the gain for TM mode light is greater than the gain for TE mode light, i.e., in reverse proportion to the polarization gain ratio for amplifier 10. In this way, the optical energy output from the combination of amplifiers 10 and 12 is substantially polarization independent. This technique can also be practiced by arranging the SOAs in parallel as described, for example, in the textbook Optical Amplifiers and their Applications, edited by S.Shimada and H. Ishio, published by John Wiley & Sons, Chapter 4, pp. 70-72, the disclosure of which is incorporated here by reference. A similar technique is described in the article entitled "Polarization Insensitive Optical Amplifier Consisting of Two Semiconductor Laser Amplifiers and a Polarization Insensitive Isolator in Series", by Koga et al., IEEE Photonics Technology Letters, Vol.1, No. 12, December 1989, pp. 431-33, the disclosure of which is incorporated here by reference. Therein, two SOAs are separated by a polarization insensitive isolator. Another technique for compensating for polarization dependent gain is to use some other corrective device downstream of the SOA as shown in Figure 2. For example, a variable polarization dependent loss control device 22 can be disposed downstream of the SOA 20 to compensate for unequal magnitudes of TE and TM gain. This technique is described in U.S. Patent No. 6,310,720, the disclosure of which is incorporated here by reference. All of these techniques suffer from, among other things, the drawback of requiring a number of additional components to create a single polarization insensitive SOA, and the lack of integration of the components, thereby increasing the cost of the solutions. For

example, the technique described in the Koga article employs a polarization insensitive optical isolator that is not amenable to monolithic integration with the two SOAs.

[0007] Attempts have also been made to provide an integrated solution to this problem, i.e., to design polarization insensitive SOAs. One such attempt is described in the article entitled "Analysis of Polarization Independent Optical Amplifiers and Filters Based on Polarization Rotation in Periodically Asymmetric Waveguides", by Mats Gustavsson, IEEE Journal of Quantum Electronics, Vol. 29, No. 4, April 1993, pp1168-1178, the disclosure of which is incorporated herein by reference. Therein, a periodically asymmetric active waveguide is used to fabricate a polarization insensitive laser amplifier. However, as seen in Fig.2 of this article, this device is only able to provide polarization insensitivity at one particular operating gain level. At other operating levels, the device is actually quite polarization sensitive. Another attempt at an integrated solution is found in U.S. Patent No. 5,982,531 to Emery et al., the disclosure of which is incorporated here by reference. Therein, the active material in the SOA is subjected to a tensile strain sufficient to render the amplifier insensitive to the polarization of the light to be amplified. However, balancing the TE/TM gain using such techniques requires extremely accurate control over device geometry, layer thickness, layer composition and background absorption loss. In practice, this level of control is very difficult to achieve in a repeatable manufacturing process, i.e., there may be a significant variance in the polarization sensitivity of SOAs manufactured using such techniques from one manufacturing run to another.

[0008] Accordingly, Applicants would like to provide techniques and devices that provide monolithically integrated, polarization insensitive SOAs in a manner which is cost effective and facilitates manufacturing repeatability.

SUMMARY

[0009] Systems and methods according to the present invention address this need and others by providing polarization insensitive semiconductor optical amplifiers. According to exemplary embodiments of the present invention, semiconductor optical amplifiers have an overall gain (i.e., from device input to device output) that is substantially independent of the polarization state of the input, i.e., less than 1 dB difference between transverse electric (TE) and transverse magnetic (TM) overall gain. This is accomplished even though portions of the active region of the SOA can have substantial (i.e. greater than 1 dB) polarization gain dependence. SOAs according to the present invention include a portion of the active region in which TE gain is enhanced and a portion of the active region in which TM gain is enhanced by, for example, varying an etch depth of the residual cladding layer thickness above each portion. For example, over a first portion of the gain section, the residual cladding layer is thinner than over a second portion of the gain section. This results in the first portion providing more gain to optical energy having a TE polarization state than optical energy having a TM polarization state. In the second portion of the gain section, however, more gain is provided to optical energy having a TM polarization state than energy having a TE polarization state. The resulting gain differences can be designed to offset one another so that the output has a gain that is substantially polarization independent.

[0010] According to one exemplary embodiment of the present invention, a semiconductor optical amplifier includes a substrate, a first gain section, disposed on the substrate, for providing a first gain to an optical signal, wherein the first gain has a first transverse electric (TE) component and a first transverse magnetic (TM) component, and a magnitude of the first TE component is greater than a magnitude of the first TM component; and a second gain section, disposed on the substrate adjacent to the first gain section, for providing a second gain to the optical signal, wherein the second gain has a second TE component and a second TM component, and a magnitude of the second TM component is greater than a magnitude of the second TE component.

[0011] According to another exemplary embodiment of the present invention, a semiconductor optical amplifier includes a substrate, a gain section, provided on the substrate, for providing gain to an input optical signal; and a residual cladding layer provided on the gain section, the residual cladding layer having a first thickness over a first portion of the gain section and a second thickness over a second portion of the gain section, the first thickness being different than the second thickness.

[0012] According to another exemplary embodiment of the present invention, a method for amplifying an optical signal includes the steps of: providing a gain section on a substrate; providing, on a first portion of the gain section, a residual cladding layer having a first thickness; providing, on a second portion of the gain section, a residual cladding layer having a second thickness, the first and second thicknesses being different from one another; amplifying the optical signal in the first portion of said gain section to generate an amplified optical signal having a transverse electric (TE) component which is greater than a transverse

magnetic (TM) component; and amplifying the amplified optical signal in the second portion of the gain section to generate a substantially polarization independent output optical signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The accompanying drawings illustrate exemplary embodiments of the present invention, wherein:

[0014] FIG. 1 depicts a conventional technique for compensating for polarization dependent gain of SOAs by employing two SOAs in series;

[0015] FIG. 2 depicts another conventional technique involving employing a downstream corrective device that adjusts the gain;

[0016] FIG. 3 depicts a conventional, ridge-type SOA having a uniform residual cladding layer thickness;

[0017] FIGS. 4(a) and 4(b) are graphs depicting the effect of varying the residual cladding layer on the gain confinement factor and loss confinement factor, respectively, in an exemplary SOA for optical energy having TE and TM polarization states;

[0018] FIG. 5 is a graph depicting gain as a function of residual cladding layer thickness for both optical energy having a TE polarization state and a TM polarization state;

[0019] FIGS. 6(a)-6(c) depict an SOA according to an exemplary embodiment of the present invention having a residual cladding layer with a first thickness over a first portion of a gain section and a second thickness over a second portion of the gain section; and

[0020] FIG. 7 is a flowchart depicting a method for fabricating an SOA according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION

[0021] The following detailed description of the invention refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. Also, the following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims.

[0022] Devices and methods according to exemplary embodiments of the present invention provide semiconductor optical amplifiers whose overall gain is substantially polarization independent, i.e., in the output of semiconductor optical amplifiers according to exemplary embodiments gain provided to input optical energy having a TE polarization is substantially equal to the gain provided to input optical energy having a TM polarization. In the context of the present invention, “substantially polarization independent” refers to a difference between TE and TM overall gain of less than 1 dB and, preferably, less than 0.5 dB. This quality of SOAs according to the present invention is achieved by, for example, providing an SOA having at least two different sections, a first section in which TE gain is greater than TM gain and a second section in which TM gain is greater than TE gain. By design, the two sections TE/TM gain differences will offset one another, such that the overall gain is substantially polarization independent. According to exemplary embodiments of the present invention, this can be accomplished by varying the thickness (etch depth) of the residual cladding layer of the SOA.

[0023] Consider the exemplary, conventional ridge-waveguide-type SOA 28 structure illustrated in the cross-section of Figure 3. Therein an active (gain) region 30 is sandwiched

between the substrate layer 32 and the residual cladding layer 34. Those skilled in the art will appreciate that any gain structure can be employed as active region 30, e.g., a buried-type device and/or bulk materials can be used to fabricate gain section 30. Multiple quantum wells (not shown) may be provided in gain section 30 using various materials, e.g., InAlGaAs, InGaAsP and InP, to create gain section 30 using well known techniques. The substrate layer 32 and residual cladding layer 34 can be formed from, for example, InP. An etch stop layer 36 is disposed on top of the residual cladding layer 34. The ridge is formed from another InP layer 38 capped by a metal electrode 40. Current is injected via electrode 40 into the SOA 28, so that gain is applied to an optical signal passing through the active region 30. However, gain is only applied in the pumped region 42 of the active region 30. Outside of the pumped region 42, where there is no pumping current, the optical signal suffers from energy absorption as it passes through the SOA 28. The input optical power P_{in} injected into the SOA 28 is amplified according to $P_{out} = G_{sp} P_{in}$, where G_{sp} is the single pass gain over the length L of the SOA 28 such that $G_{sp} = e^{g_{net} L}$. The net gain g_{net} is given by $g_{net} = \Gamma g - \alpha$ where Γ , g , and α are the optical confinement factor, the material gain and the optical loss, respectively. The optical loss can be further expressed as the sum of fixed and variable components: $\alpha = \Gamma_{up} \alpha_{up} + \alpha_{bg}$ where Γ_{up} , α_{up} , and α_{bg} are the optical loss confinement factor, optical loss in the unpumped region, and fixed background optical loss, respectively. The optical loss increases as the amount of optical energy overlapping the unpumped region (Γ_{up}) increases.

[0024] The beam shape and/or size of the optical signal as it passes through SOA 28 is typically referred to as the “mode”. The mode of an optical signal changes based upon its

polarization state as shown in Figure 3. This results in the TE mode 44 extending further outside of the pumped region 42 than the TM mode 46.

[0025] Applicants have discovered that by changing the thickness of the residual cladding layer 34, the gain received by both the TM mode energy and the TE mode energy changes. Moreover, the change in TM mode energy gain and the change in TE mode energy gain are different as a function of residual cladding layer thickness. Consider the graphs of Figures 4(a) and 4(b), which reflect Applicants' testing of devices having different residual cladding thicknesses. In Figure 4(a), the gain confinement factors are plotted versus residual cladding thickness for both TE mode energy (upper line) and TM mode energy (lower line). This graph shows that as the residual cladding layer thickness increases, the gain confinement factors for both TE mode energy and TM mode energy decrease, but that the gain confinement factor for TE mode energy decreases more rapidly than the gain confinement factor for TM mode energy as a function of increasing residual cladding layer thickness. Similarly, the loss confinement factor (Figure 4(b)) increases for both TE mode energy and TM mode energy with increasing residual cladding layer thickness, however the rate of increase is less for TM mode energy than it is for TE mode energy. This data confirms that as the residual cladding thickness increases, the gain applied to the TE mode energy drops off faster than the gain applied to the TM mode energy. This property can be applied, according to exemplary embodiments of the present invention, to fabricate SOAs that are substantially polarization independent.

[0026] Initially, Applicants tested a number of SOAs having different residual cladding thicknesses in order to quantify the differences in TE mode gain vs. TM mode gain.

Exemplary results are plotted in the graph of Figure 5. Therein, it can be seen that the TE mode gain is significantly higher than the TM mode gain for residual cladding layer thicknesses of less than 0.3 micrometers, but falls off more quickly than the TM mode gain such that the gains are approximately equal at about a residual cladding depth of 0.35 micrometers (referred to below as the “crossover gain point”). Then, for residual cladding thicknesses of more than about 0.35 micrometers, the TM mode gain is greater than the TE mode gain. Those skilled in the art will appreciate that devices employing different materials, fabrication processes, etc. may have different crossover gain points and TE/TM gain characteristics than the example provided in Figure 5.

[0027] Using this type of data, a substantially polarization independent SOA 60 can be fabricated from two sections as shown in Figure 6(a). In this side view of an SOA according to an exemplary embodiment of the present invention, a first section 61 has a TE gain which is greater than its TM gain and a second section 63 has a TM gain which is greater than its TE gain. Figures 6(b) and 6(c) are cross-sectional views of SOA 60 taken across section lines B and C, respectively, in Figure 6(a). In Figures 6(a)-(c), from top to bottom, the SOA 60 includes a metallization layer 62, an InP layer constituting the ridge 64, a residual cladding layer 66, an active (gain) region 68 and a substrate 70. By selecting a first residual cladding thickness T_1 for the first section 61, i.e., wherein the first thickness is less than the crossover gain point, and a second residual cladding thickness T_2 for the second section 63, i.e., wherein the second thickness is greater than the crossover gain point, the polarization gain differences will offset one another. Returning to Figure 5, it can be seen that, for example, selecting a first residual cladding layer thickness T_1 of about 0.3 micrometers will

provide the first section 61 of the SOA 60 with approximately a 4 dB difference between TE gain and TM gain, with TE gain > TM gain. Then by selecting a second residual cladding layer thickness T_2 of about 0.4 micrometers, the second section 63 will also have approximately a 4 dB difference between TE and TM gain, but with TM gain > TE gain. Those skilled in the art will appreciate that, for different implementations, these respective residual cladding layer thicknesses can be less than 0.3 micrometers and more than 0.4 micrometers, respectively.

[0028] A method for fabricating SOAs according to an exemplary embodiment of the present invention is depicted in the flowchart of Figure 7. Initially, at step 70, the structure is grown or deposited using conventional semiconductor fabrication techniques, with the exception that two etch stop layers are provided above the active region, i.e., one for each of the two thicknesses of the residual cladding layer. Once the structure is grown or deposited, the ridge portion of the device is protected using, for example, a nitride mask at step 72. Then, at step 74, the portions of the SOA on either side of the ridge are etched down to the first etch stop layer, i.e., such that the residual cladding layer then has a thickness T_2 . The first etch stop layer is then removed (step 76) and the portion of the residual cladding layer within the second section (TM enhanced) is protected by, for example, application of a photoresist layer at step 78. Then, the first section's residual cladding layer can be further etched so that its thickness becomes T_1 at step 80.

[0029] Applicants' initial testing indicates that reflections at the etch boundary, i.e., between the first section 61 and second section 63, are not a significant concern. If, however, various implementations of the present invention result in significant reflection of optical

signal energy at the etch boundary, then one of the sections can be positioned at an angle relative to the other to reduce reflections. Alternatively, the active waveguide in the first section 61 can be connected to the second section 63 using an integration technique, for example, employing a resonantly coupled set of active and passive waveguides. More details regarding this type of integration technique using resonantly coupled devices *per se* can be found in U.S. Patent No. 6,310,995 (the “995 patent”), the disclosure of which is incorporated here by reference.

[0030] The above-described exemplary embodiments are intended to be illustrative in all respects, rather than restrictive, of the present invention. Thus the present invention is capable of many variations in detailed implementation that can be derived from the description contained herein by a person skilled in the art. All such variations and modifications are considered to be within the scope and spirit of the present invention as defined by the following claims. No element, act, or instruction used in the description of the present application should be construed as critical or essential to the invention unless explicitly described as such. Also, as used herein, the article “a” is intended to include one or more items.